RECENT PROGRESS IN HEEL-STRIKE GENERATORS USING ELECTROACTIVE POLYMERS

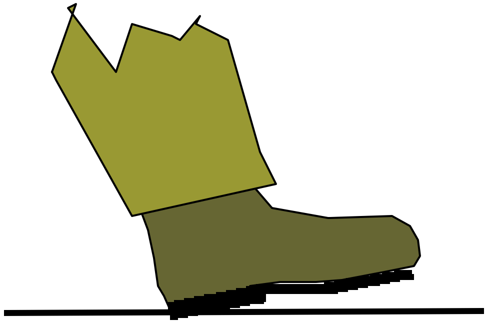
Ron Pelrine

Roy Kornbluh

SRI International

Project Goals and Milestones

- Demonstrate and establish dielectric elastomer (DE) generator technology
- Develop and demonstrate a suitable DoD application - i.e. a heel-strike generator
- Explore other DoD generator applications where DE technology would be advantageous
- Some specific milestones:
  - demonstrate energy production using DE generator (May 1999)
  - demonstrate 1 W boot generator (end of Phase I; May 2000)
  - demonstrate 2.5 W boot generator (end of Phase II)



Heel-Strike Generator

Backpack Generator

Heel-Strike Generator - Available Power and Applications

- Maximum estimated output depends on mechanical assumptions
  - assume 1000 N force acting over 2-4 mm stroke
  - boot and shoe data indicate 35% - 65% of the energy is returned as elastic rebound energy
  - best estimates indicate 0.7 - 2.6 J are available for conversion per step
  - other factors may increase the estimate; e.g. backpack weight, optimized designs, secondary sources such as shoe flexures
  - conversion losses are probably the most significant in derating the available power to the actual power output; typical estimate is 1-2 W
- Boot-specific and general purpose
  - boot-specific applications use and/or store power locally; examples:
    - inertial navigation
    - emergency backup power; emergency transponders
    - many "blue sky" applications
  - general purpose power for the soldiers' radios, computers, etc.
    - requires a convenient, UNOBTRUSIVE, means for transmitting power to belt batteries

Heel-Strike Generator - General Requirements

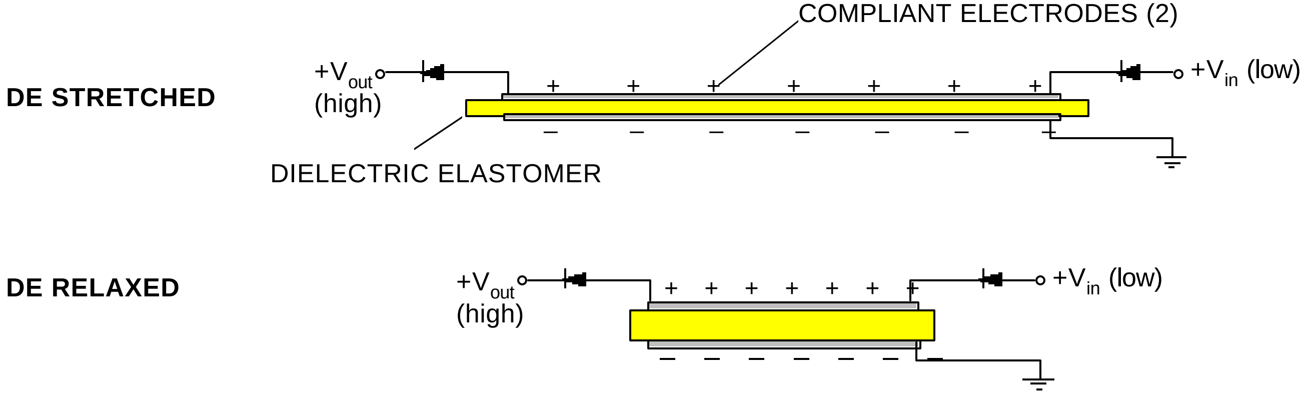
- Critical that added weight be zero or negligible
  - boot heel volume is roughly 150 cc’s
  - derate to 80 cc’s for generator; assume 60 cc’s for polymer, and 20 cc’s for electronics (strawman parameters)
  - polymer densities typically 1 g/cc; some air volume needed for expansion/contraction of polymers; electronic density probably around 2-3 g/cc overall depending on specifics

- Generator must be quiet
  - no acoustic noise
  - no electromagnetic noise

- Other specs
  - rugged
  - waterproof
  - low cost

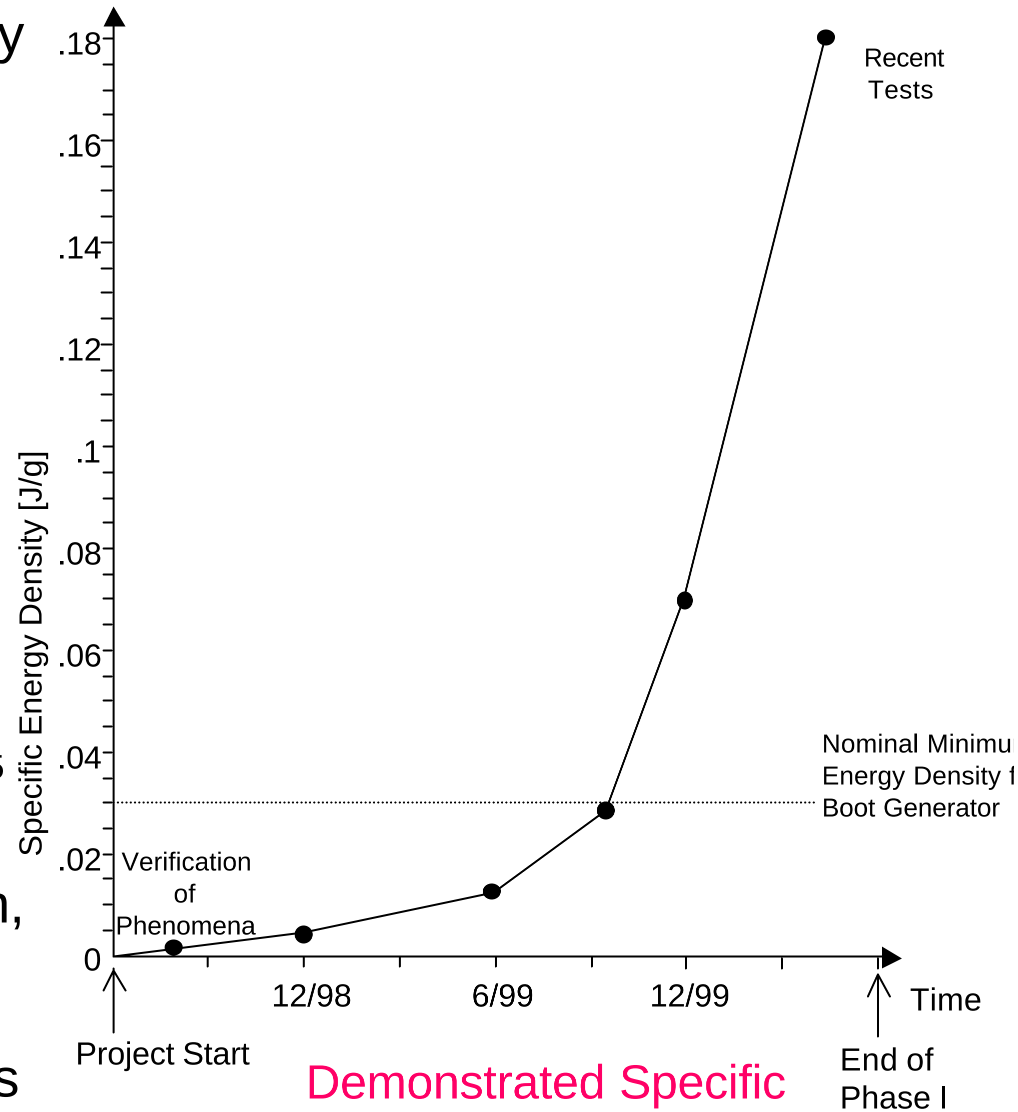
Approach: Dielectric Elastomer Generators

- Energy is generated due to a change in the capacitance as the film is stretched
  - $E = \frac{1}{2} Q_o^2 (1/C_f - 1/C_i)$
  - nearly incompressible polymers increase in area and decrease in thickness when stretched



Why Dielectric Elastomer Generators?

- High theoretical specific energy densities, over 1.5 J/g
- Low cost materials
- High potential efficiencies and coupling factors
- Compliance offers interesting load coupling advantages for many applications; can be operated with little or no leverage between input stroke and material strain
- Low leakage losses; resistivities typically 10^{14} - 10^{15} ohm-cm
- Can be operated as high strain, low pressure actuators; may offer interesting active control and smart structure capabilities

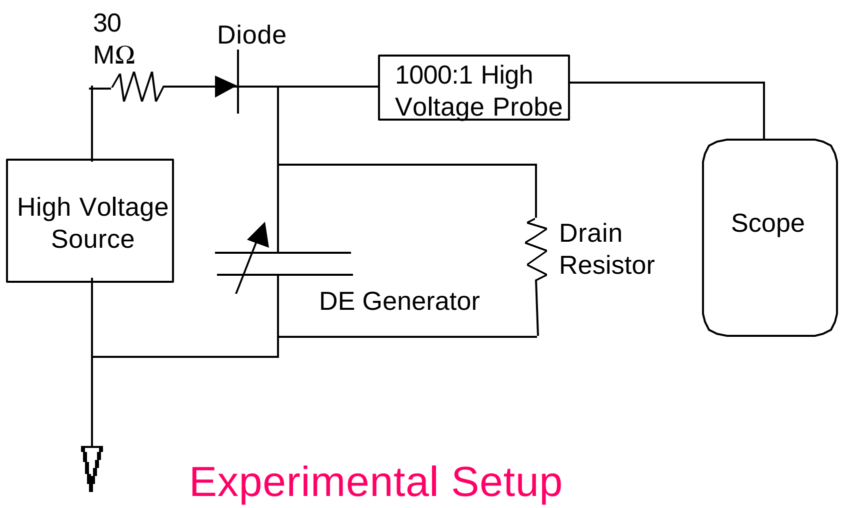


Demonstrated Specific

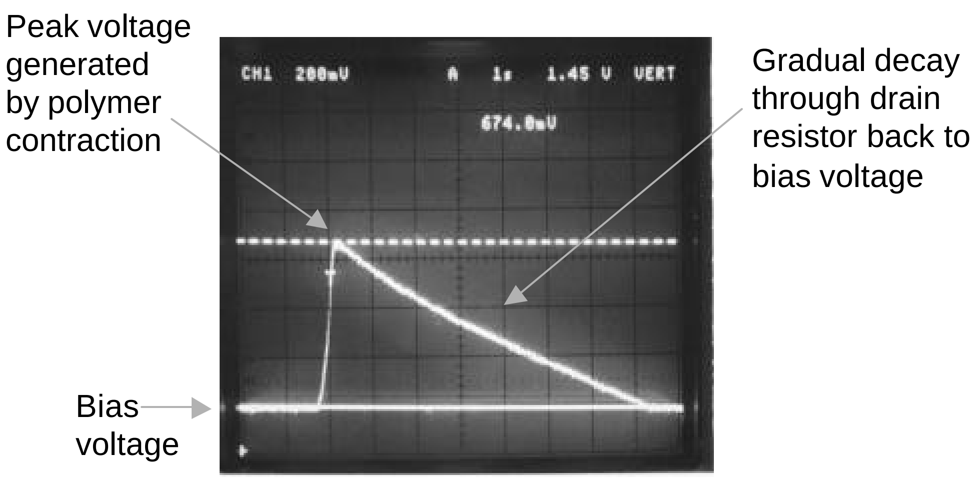
Experimental Setup

- Mechanical setup to allow pre-set strains between expanded and contracted states

- Electrical setup to measure voltage changes
  - can also use to measure currents through known resistors
  - non-contact electrostatic voltmeter (EV) used to measure leakage directly (no high voltage probe)



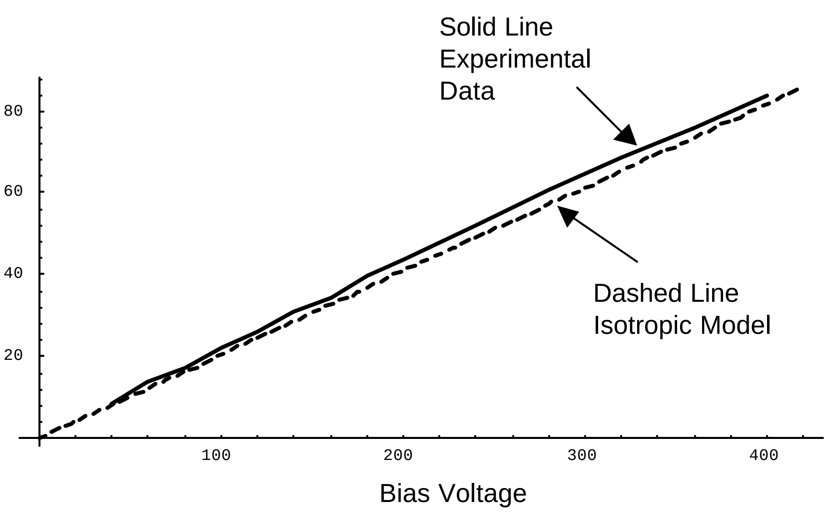
Experimental Setup



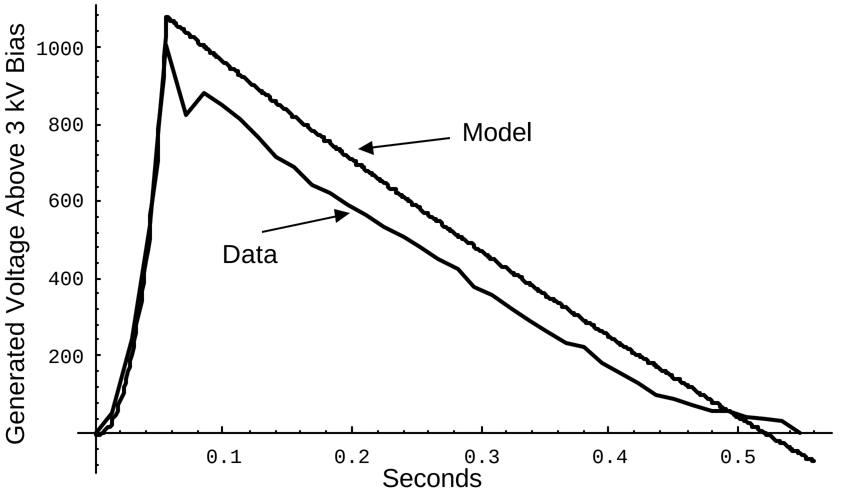
Example Data

Model Comparison

- Demonstrated good agreement between measured output and model output



Comparison Between Model and Data Using Different Bias Voltages



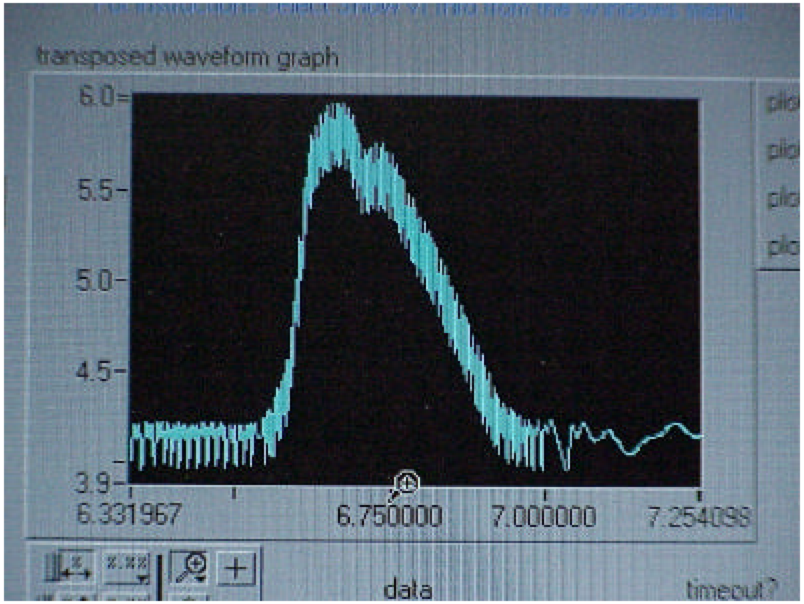
Time Domain Comparison Between Model and Data at 3 kV Bias and Draining Through a 500 MΩ Resistor

New DE Materials

New elastomer materials

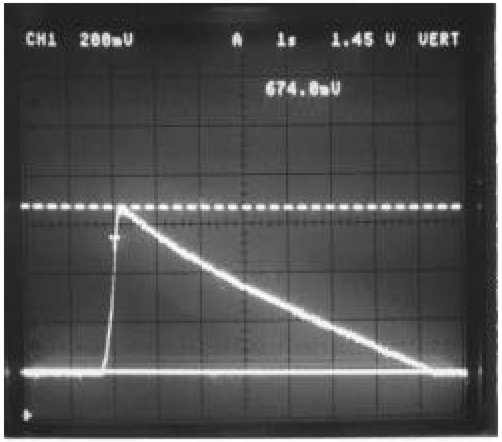
- higher breakdown strengths; up to 400 V/µm
- higher dielectric constants 4.8 (vs. 2.8 for silicone)
- actuator tests indicate over 3 J/g energy density
- acceptable viscoelastic losses and resistivity

Data indicating 0.18 J/g energy density using new elastomers (input bias: 4.2 kV output: 5.8 kV)

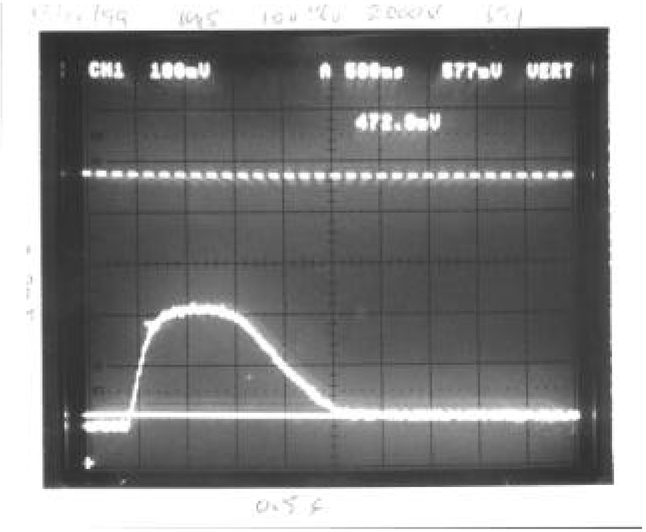


Experimental Verification of Higher Efficiency Regime

- Field pressures need to be comparable to mechanical stresses in boot generator
  - lower field pressures generally indicates poor conversion efficiency
  - boot generator needs to have some rebound energy
  - experimental signature is a rounded voltage output at higher bias



1000 V bias



2000 V bias

Electronics

- Relatively high voltages are needed to maximize energy density while keeping the film thickness reasonable

- General sequence:

  (1) film is stretched

  (2) electrical energy is placed on film in stretched state

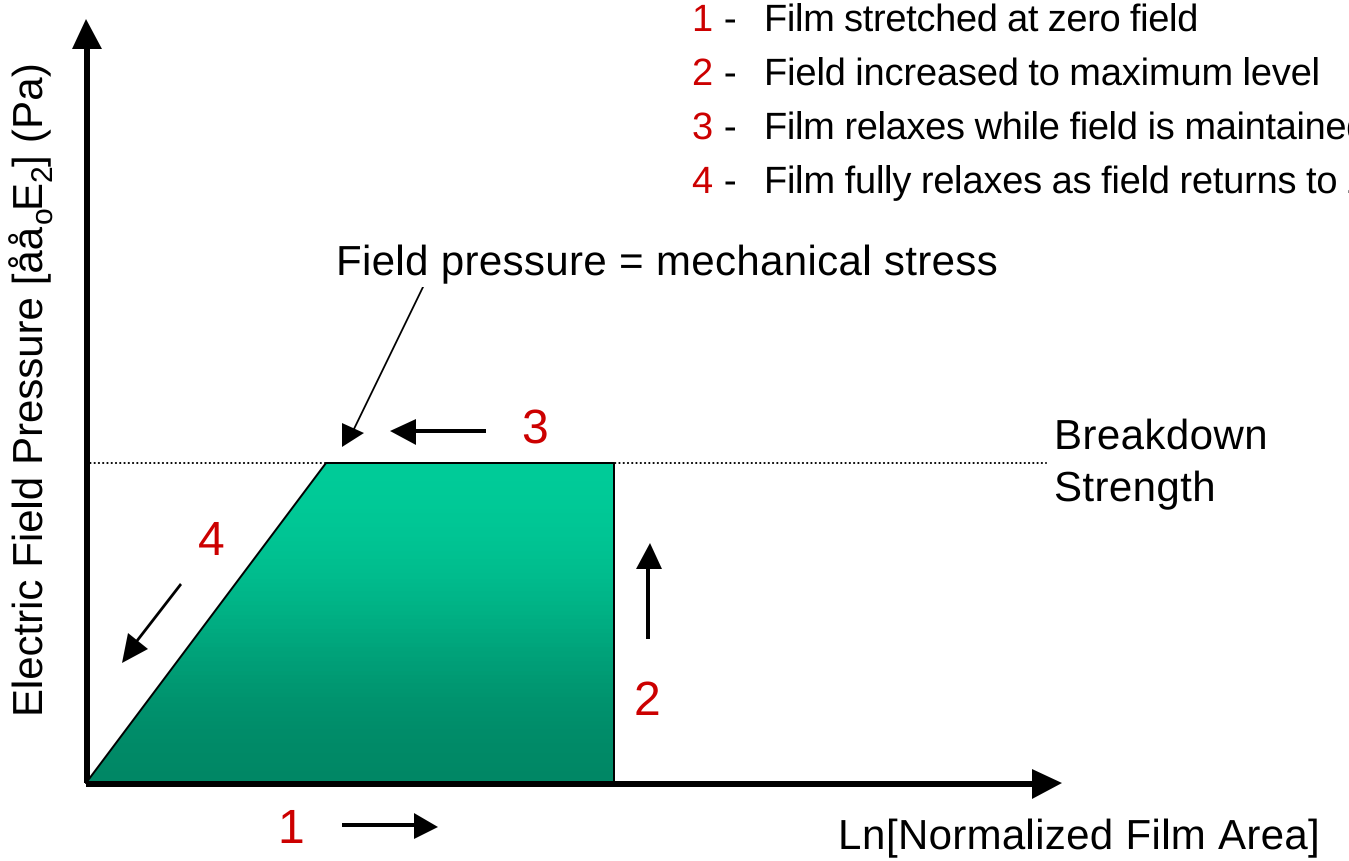
  (3) film contracts

  (4) electrical energy is removed from film in contracted state

  - energy may be removed during contraction, or added during stretching
  - critical that most of the electrical energy be removed prior to stretching; otherwise, material acts as an actuator and converts mechanical-to-electrical energy, reducing the generator’s energy density

Example: Potential Cycle for DE Generator

1 - Film stretched at zero field
2 - Field increased to maximum level
3 - Film relaxes while field is maintained near maximum
4 - Film fully relaxes as field returns to zero



Step-up Conversion

- Step-up voltage for charging is not a major issue
  - designs exist where step-up only needs to supply initial charging and offset leakage
  - step-up only needs to supply 5-10% of total output power in some designs
  - even low efficiency step-up can have minimal impact on overall efficiency
  - commercial step-up converters exist in sugar-cube size up to 5 kV

Step-down Conversion

- Two approaches are being investigated:
  - inverter
  - commercial converters in series

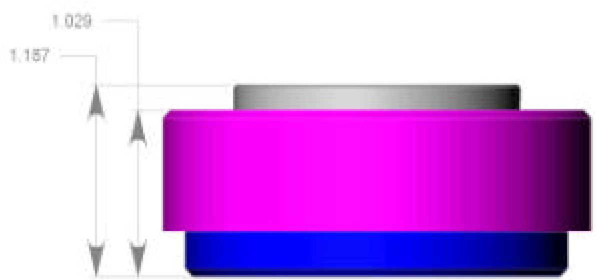
- Commercial converters for stepping down 350 V to 5 V
  - used in series arrangement to step down virtually any voltage
  - not appropriate in long term because of size
  - significant transient losses
  - currently a backup approach

Inverter Approach

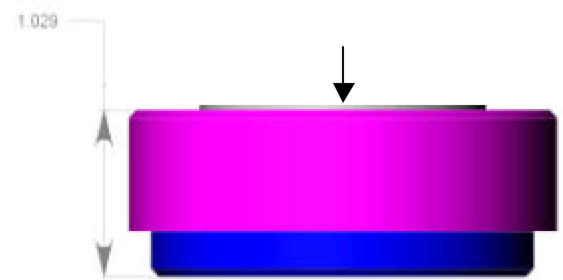
- Switch high voltage DC through a step-down transformer
  - transformer and high voltage switch are critical components
  - high frequencies typically used (e.g. 10-100 kHz)
- Small transformers tested up to 800 V with 75-80% step-down efficiency
  - up to about 20 W output
  - voltage currently limited by equipment
- Single transistors up to 1600 V
  - can be cascaded for higher voltage if needed
  - we have demonstrated 5 kV switching
    (rise time<1 μs; fall time 20 μs)

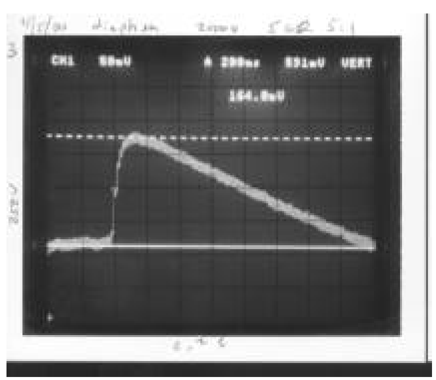
Mechanical Design

- Many different mechanical designs have been investigated
- Higher performing materials allow simpler, lower risk mechanical designs
  - less film is needed



Stepping Force Stretches DE film





Preliminary data:
2000 V bias, 2800 V output

Summary

- Dielectric elastomers are a promising new generator technology for lightweight, high energy density generators and actuators
- Good material performance has been demonstrated
- Focus is on heel-strike generators - a good match between properties and application
  - other generator applications are also attractive, e.g. backpack and conventional generator applications
  - electronics focus is on step-down inverter (primary approach) and commercial converters (backup approach)
  - simple mechanical design has been completed and initial testing begun